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## Technical Memorandum 79538

# Engineering A Laser Remote Sensor for Atmospheric Pressure and Temperature

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**ABSTRACT**

A system for the remote sensing of atmospheric pressure and temperature is described. Resonant lines in the 7600 Angstrom oxygen "A" band region are used and an organic dye laser beam is tuned to measure line absorption changes with temperature or pressure. A reference beam outside this band is also transmitted for calibration. Using lidar techniques, profiling of these parameters with altitude can be accomplished.

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# ENGINEERING A LASER REMOTE SENSOR FOR ATMOSPHERIC PRESSURE AND TEMPERATURE

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## INTRODUCTION

Although experiments for the radiometric determination of the earth's surface or cloud top temperatures have been conducted from earth orbit to a fair degree of accuracy, no such technique, active or passive, has been demonstrated for atmospheric pressure. In the case of temperature, passive remote sensing techniques can obtain vertical resolutions only on the order of a scale height with temperature accuracy of only two to three degrees centigrade. This paper will describe the basic design of a system employing CW lasers that will be used for determining pressure and temperature remotely. This system leads to a lidar system for profiling of these parameters with 1-2 km resolution and better than 0.3% accuracy for pressure and 0.5 K accuracy for temperature.

Radiation passing through the atmosphere will be selectively absorbed and scattered by aerosols and gas molecules as a function of emission frequency. In general, the absorption is critically dependent on both the frequency and the spectral bandwidth of the radiation. Over narrow spectral ranges (several wavenumbers) this dependence generally does not arise from aerosol effects, which are relatively constant, but from line resonances of the gas molecules. Because of these resonances, a tuneable narrow-band laser transmitted over an atmospheric path could produce either a strong or a weak signal as its frequency is varied over a spectral interval less than a wavenumber. In order to investigate the effects of individual resonant absorption lines, the spectral bandwidth of a tuneable laser generally needs to be on the order of the width of a spectral line, i.e.,  $0.1 \text{ cm}^{-1}$  (3 GHz).

Each constituent gas in the atmosphere has its own characteristic spectral signature. The width and shape of these lines depends on several factors, including the gas pressure and temperature. A technique to separate out and minimize the interdependence of these parameters has been presented by L. Korb at the 8th International Laser Radar Conference sponsored by the American Meteorological Society. The experiment described herein has been designed to verify the basic assumptions in this technique in as efficient and rapid a manner as possible. The need for rapidity is to allow for flexibility in scheduling a pulsed system for testing on the Space Shuttle, preliminary aspects of which have already begun.

### THEORY

The spectral absorption of gases in the atmosphere can be described in general by the Voigt line profile. At the higher pressures found near the earth's surface, however, the rather complicated functional dependence of the Voigt profile reduces to a Lorentzian profile:

$$P(\bar{\nu}, \alpha_L) = \frac{1}{\pi} \frac{\alpha_L}{(\bar{\nu} - \bar{\nu}_0)^2 + \alpha_L^2} \quad (1)$$

where  $\bar{\nu}_0$  is the line center frequency in wavenumbers, and  $\alpha_L$  is the Lorentzian half-width at half maximum of the line. Kinetic theory gives the functional dependence of the line width as

$$\alpha_L(p, T) = \alpha_{L_s}(p_s, T_s) \left( \frac{p}{p_s} \right) \left( \frac{T_s}{T} \right)^{1/2} \quad (2)$$

where  $\alpha_{L_s}(p_s, T_s)$  is the Lorentzian half-width at half maximum at standard temperature and normalized to unit pressure. Values used for  $\alpha_{L_s}(p_s, T_s)$  are found empirically.



The intensity,  $I$ , of a spectrally narrow laser beam,  $I_t$ , transversing a path,  $d$ , is

$$I \propto \frac{I_t}{d^2} e^{-\int_0^d (\zeta + \bar{k}) dr} \quad (\text{far field}) \quad (3)$$

where  $\bar{k}$  is the resonant absorption coefficient per unit length, and  $\zeta$  is the total extinction coefficient per unit length due to non-resonant effects. Functionally,

$$\bar{k} = q n_0 S(T_s) \frac{p}{p_s} \left( \frac{T_s}{T} \right)^2 P(\bar{\nu}, \alpha_L) e^{-(E/kT_s)(\frac{T_s-T}{T})} \quad (4)$$

where  $q$  is the mixing ratio of the resonant absorbing species;  $S(T_s)$  is the line strength at standard temperature (determined empirically);  $n_0$  is the number of molecules per unit volume at STP; and  $E$  is the initial energy state of the transition.

By finding the derivative of  $\bar{k}$  with respect to temperature, it can be shown that the sensitivity of the measurement to temperature can be minimized at a given temperature by selection of a line with the proper initial energy level. In addition, by making measurements far enough in the line wing such that  $(\bar{\nu} - \bar{\nu}_0)^2 \gg \alpha_L^2$ , the laser intensity,  $I_w$ , propagating over a path of constant molecular parameters can be approximated as a function of pressure as

$$I_w \propto \frac{I_{tw}}{d^2} e^{-[\zeta + c p^2] d} \quad (5)$$

where  $c$  is a constant.

For practical application in obtaining a physically meaningful pressure measurement, a second laser beam at a nearby frequency is required. We will call this the reference beam and the first laser beam described above will be the wing beam. The two beams must be located close enough in frequency such that the same continuum effects will be seen by

both, but the reference beam must, however, be located away from any resonant lines to avoid their effect. For this case, the reference beam would have an attenuation

$$I_r \propto \frac{I_{tr}}{d^2} e^{-\xi d} \quad (6)$$

over a path of constant parameters. If the beams are chosen properly,  $\xi$  will be the same at both frequencies. The reference beam,  $I_r$ , needs only to be spectrally narrow enough to avoid capturing atmospheric absorption lines under its profile. Given these conditions, the ratio of the two beams is

$$\frac{I_r}{I_w} = \frac{I_{tr}}{I_{tw}} e^{+cp^2 d} \quad (7)$$

Inverting for pressure:

$$p = \left[ \frac{1}{cd} \ln \left( \frac{I_r/I_w}{I_{tr}/I_{tw}} \right) \right]^{1/2} \quad (8)$$

## EXPERIMENT

In order to conduct these experiments, suitable atmospheric absorption lines with the proper energy levels and with nearby line-free regions are required. In addition, tunable lasers that emit at the proper frequencies are, of course, also required. For the pressure experiments, the use of the Oxygen "A" band, so called because it is spectrally intermingled with telluric lines long designated "A" in the solar spectrum, was decided upon. This band starts near 7600 Angstroms and continues to about 7700 Angstroms. Lines of the necessary energy level for the range of surface temperatures that are expected for this experiment are found near 7600 Angstroms, while a spectral area clear of lines is found nearby at 7590 Angstroms which can be used for the reference line region. These locations are sufficiently close such that scattering from aerosols and molecules are similar in

their effects on the two lines and will, to first order, cancel. Corrections for higher order spectral scattering effects will, however, also be made.

Selection of the "A" band spectral region was critically dependent on finding a laser that could be tuned to emit at precisely the desired frequencies. Organic dye lasers not only meet this criterion, but are also commercially available at relatively low cost with CW output of relatively high power. Thus it was determined that the initial demonstration of the pressure and temperature measurements could be best performed using these lasers to conduct long horizontal path experiments in the atmosphere, as described below. In addition, the use of horizontal paths also allows in-situ measurements of pressure and temperature to be easily made for necessary ground truth purposes.

The experiment will be conducted at the Goddard Optical Research Facility (GORF) using the 30" Cassegrainian telescope. This telescope is located on the second floor of a dedicated observatory structure (see Figures 1 & 2). A two story unit, the first floor is a lab area with a periscope type beam steering housing which can bring laser beams generated on this level up to the telescope level. There, the beam is transmitted along the side of the telescope and parallel to the focal axis. The steering unit is so structured that the laser beam direction tracks the movements of the telescope. Targets at one and at three and a half kilometers will be used as the reflecting surfaces for the horizontal path experiment. The target surface will consist of 3M Co. encapsulated lens sheeting (#2870) which has a retro-reflective surface with a return divergence of less than half of a degree. Other structures are also available for housing the laser transmitters for future bistatic CW experiments which will be discussed in the concluding section below.

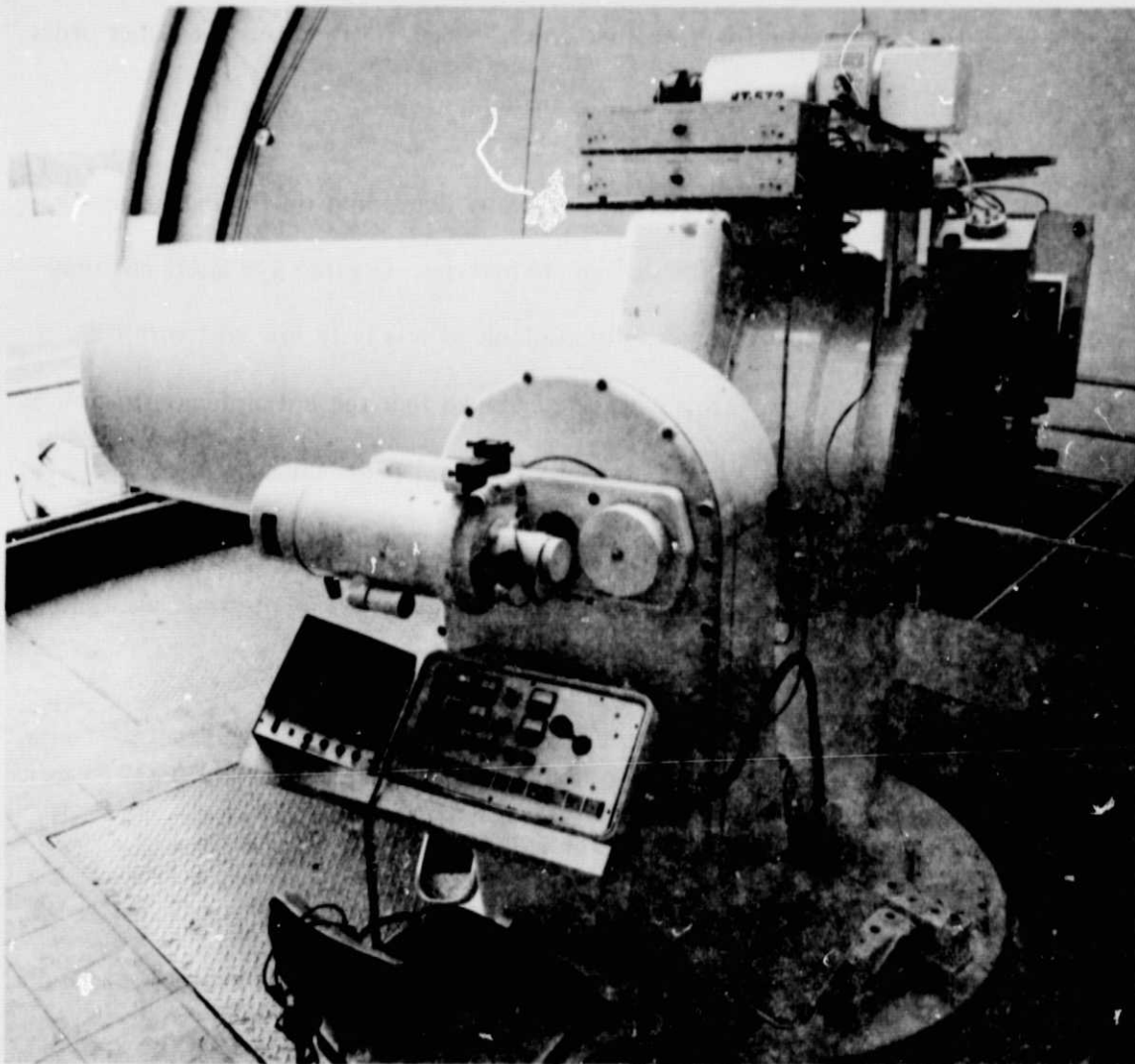


Figure 1. 30" telescope with automatic computer control console. Manual control can be accomplished using the "joy stick" on the console when the computer is switched out.

### LASERS

For any laser selected, it is necessary that there be frequency stabilization since otherwise changes in attenuation caused by frequency shifts would be confused with pressure induced changes in absorption. By sitting in the "saddle" between two adjacent lines of



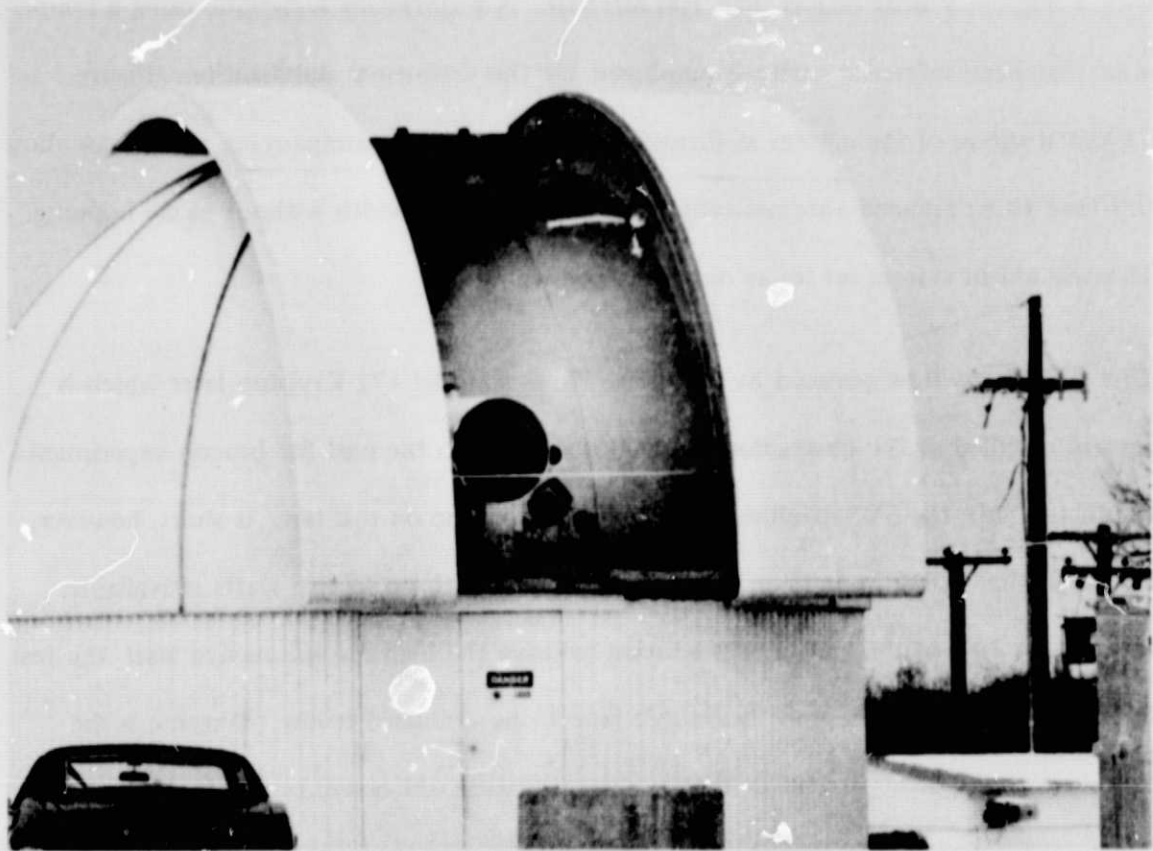


Figure 2. Observatory at the Goddard Optical Research Facility showing the telescope in the horizontal position to be used initially.

the proper energy, this sensitivity to emission frequency jitter can be greatly reduced. For this experiment, the emission frequency will be located between two lines approximately one half wavenumber (15 GHz) apart which gives sufficient accuracy for emission frequency jitter up to 300 MHz.

A laser that is expected to greatly exceed the required resolution and stability in the "A" band region from Coherent, Inc. will be used. This is the model CR 599 tuneable dye laser. This laser has an effective line width (jitter plus resolution) of less than 2 MHz



with a frequency drift of less than 100 MHz/Hr. A proprietary technique using a temperature stabilized reference cavity is employed for this frequency stabilization. Figure 3 is a block diagram of the system as furnished by Coherent. Accompanying electronics allow this laser to be scanned automatically over a 30 GHz bandwidth without mode hopping. This will aid in system set up as described below.

This dye laser will be pumped by a Spectra Physics Model 171 Krypton laser which is already installed at the observatory. It has been used in the past for beacon experiments conducted with the SMS satellite. The total logged time on this laser is short, however, and single line TEM<sub>00</sub> emission at 6471 Angstroms with up to five watts is available. Only about 70% of this power will be used to drive the high resolution dye laser, the rest being diverted to the reference beam dye laser to be discussed below. Oxazine is the organic dye with 35% efficiency. Bandwidth narrowing optics will probably reduce this to about 2% total efficiency (pump laser power in to dye laser power out). This compares favorably with most lasers with the exception of CO<sub>2</sub>. The laser beam width is 0.5 mm with a divergence of 1.6 mrad.

As mentioned above, a reference beam laser will also be pumped by the Krypton laser. This unit will be a Coherent model CR 595 organic dye laser which uses a mechanically tuneable cavity and etalon system. The primary difference between this laser and the high resolution laser is its lack of active stabilization. Short term line width for the reference laser is 40 MHz with the etalon installed, and 40 GHz using only a three plate birefringent filter. Removal of the etalon increases output power by a factor of about three. Depending on the specific nature of the spectral region just outside the "A" band where

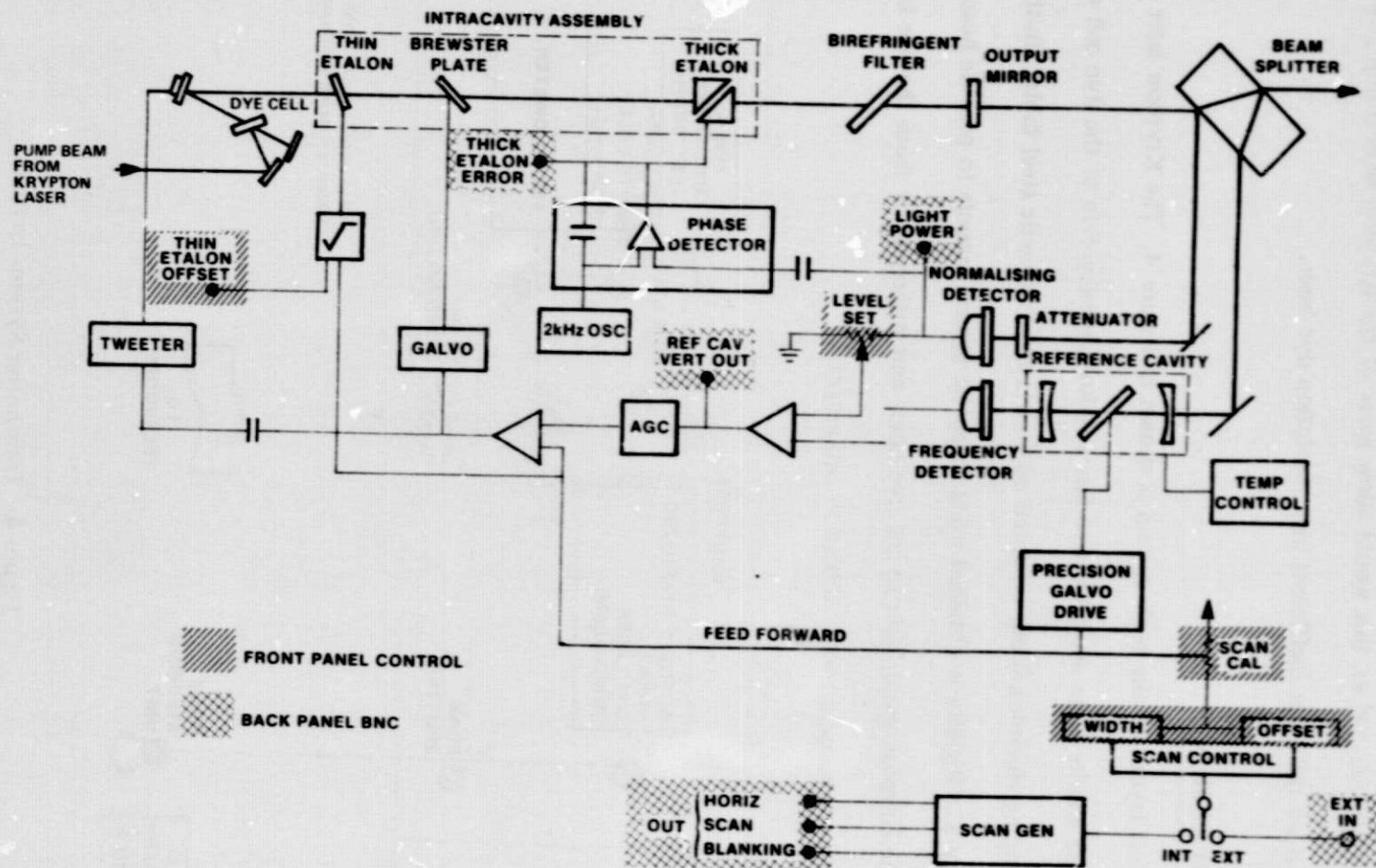


Figure 3. Internal diagram of high resolution CR 599 dye laser.

this laser will be used, operation without the etalon in the higher power, wider band mode would be possible. If so, this would allow more of the Krypton laser pump power to be used to drive the more inefficient high resolution dye laser.

### SYSTEM DESIGN

An optical layout of the basic system is shown in Figure 4. The Krypton laser is mounted on a rigid granite table while the dye lasers (with the exception of the dye cell reservoirs and scanning electronics) are mounted on a rigid ferromagnetic steel table. Both tables are 3' by 8'. Rigidity is obtained using magnetic optical mounts to provide beam control from the Krypton pump laser to the dye lasers and subsequently from the dye lasers to the telescope periscope and calibration equipment.

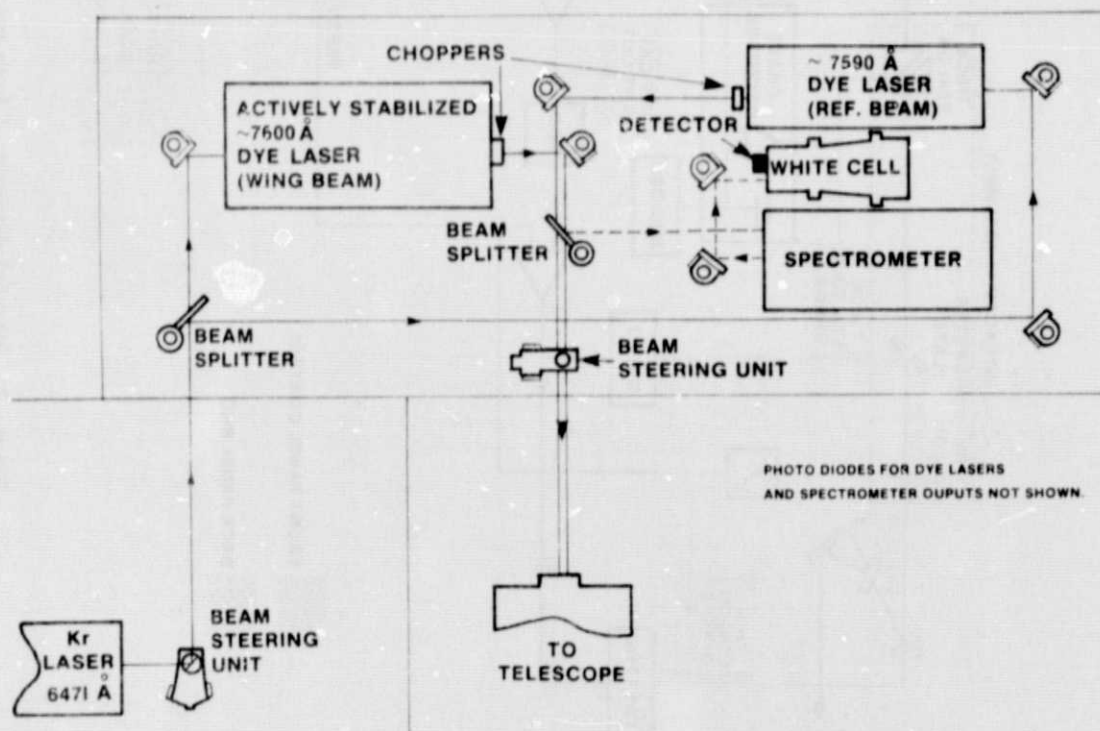


Figure 4. Transmitter System Layout.



Output from each dye laser is chopped at a different frequency using tuning fork choppers set for 150 and 400 Hz. Wavelength selection is accomplished using a combination of a small, portable spectrometer and a sealed cell containing mirrors on a 0.25 meter baseline able to simulate a 10 meter path length through multipasses, i.e., a 0.25 meter White Cell. The spectrometer is used as a coarse wavelength selector to allow the wavelength to be set to an accuracy of 0.5 Angstroms. This allows identification of the required lines and is sufficient for setting the wavelength of the reference beam. Fine tuning of the high resolution beam is accomplished using spectral scans of the output of the laser after passing through the white cell which will be filled with pure oxygen.

A photovoltaic cell will be used to continuously monitor each dye laser's output. A diffuser is mounted in front of the cell and the cell is located in close proximity to the laser in order to minimize spurious spatial effects so that only amplitude variations in the laser will be measured. Output from these cells will be used in the data acquisition system.

At the focal point of the telescope, a Varian model VPM-192M photomultiplier tube receives the simultaneous returning beams. A 30 Angstrom bandpass filter is mounted in front of the PMT to pass only the 7580 to 7610 Angstrom region, thus suppressing most of the ambient radiation while passing both reference and wing beams. The output of the PMT is divided between two Ithaco Dynatrac 391 lock-in amplifiers synchronized to the chopping frequencies of each laser. See Figure 5. Overall system calibration will be performed periodically at the point where the beams leave the observatory. This system will also consist of a diffuser/detector arrangement coupled to the lock-in amplifiers through separate lines.

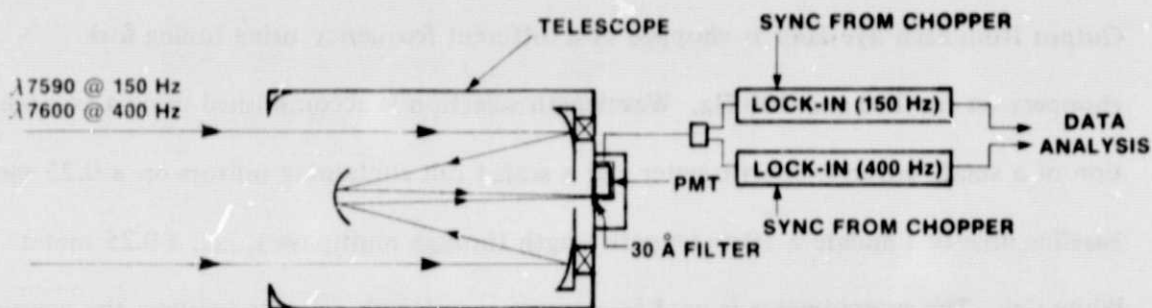


Figure 5. Receiver System.

### DATA ACQUISITION & ANALYSIS

The signals from the photovoltaic detectors and lock-in amplifiers will be used for the determination of pressure. Because of the slow nature of changes in barometric pressure, integration times can be easily adjusted to give real time readouts. Initially, a Hewlett-Packard 9825 calculator will be the controller in a data acquisition and storage system with real time strip chart readout under calculator control. See Figure 6. Signal lines from the lock-in amplifiers and solid state detectors will be hardwired into an HP 69433A

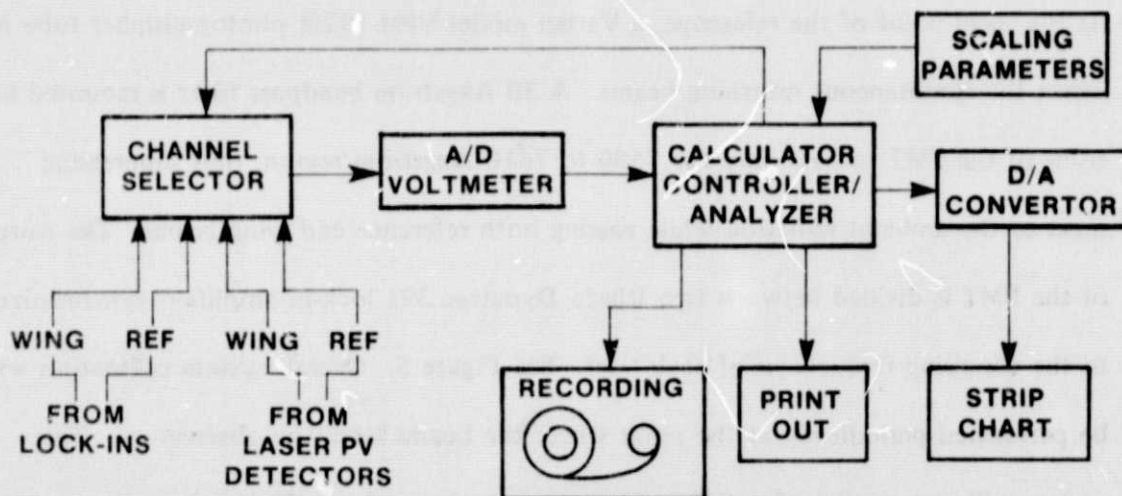


Figure 6. Data Acquisition System.



relay output/readback card which is part of the HP 6940B multiprogrammer. Under calculator control, these lines will be selectively switched to either of two HP 69421A voltage monitor cards, also part of the multiprogrammer. These cards are analog to digital converters, the difference between the two being in the range each is designed for (+1.0235 to -1.0240 volts and +10.235 to -10.240 volts with least significant bits of 0.5 mV and 5 mV respectively). Readings at rates up to 150 channels per second are fed into the 9825's memory where they can be operated upon to solve Eq. 8. A sequence of signals may be collected and averaged and various constants can be used to produce an actual readout of pressure. Either raw or modified data can be written on the 9825's digital cartridge for later transfer to magnetic tape, using an IDEAS, Inc. 4608 tape unit, which is the only unit currently on the IEEE-488 bus, for subsequent analysis on the 9825 or on the NASA/GSFC IBM 360 computers.

Data output in realtime can be accomplished in various ways: Most directly would be a timely listing of pressures. The HP 6940B multiprogrammer with a 12 bit D/A voltage convertor card can be used to drive a strip chart recorder, or the HP 9872 plotter can be used directly. In addition, investigation of the possibility of in-house development of a dedicated microprocessor to determine the pressure given the four data signals has begun. Preliminary findings are quite positive.

### CONCLUSION

A pressure experiment has been described. A similar experiment to determine temperature can be conducted in the same spectral region, allowing for the use of the same dye lasers, using high energy, thus highly temperature sensitive lines. The temperature experiment

would only require the use of a different spectral filter and the remainder of the system would be the same. A different algorithm, which will not be gone into here, would then be used for temperature readout.

Following the pressure experiment as described above, plans call for moving of the laser systems to a nearby lab area which has optical access to a 40 foot tower. From here, the beams can be sent out and the 30" telescope used to detect the return signals in the same manner as is planned for the target retroreflectors, but in this case attempts will be made to receive signals from their aerosol backscatter. See Figure 7. These weaker signals will then be studied and pressure determined. This step would lead to the lidar system which

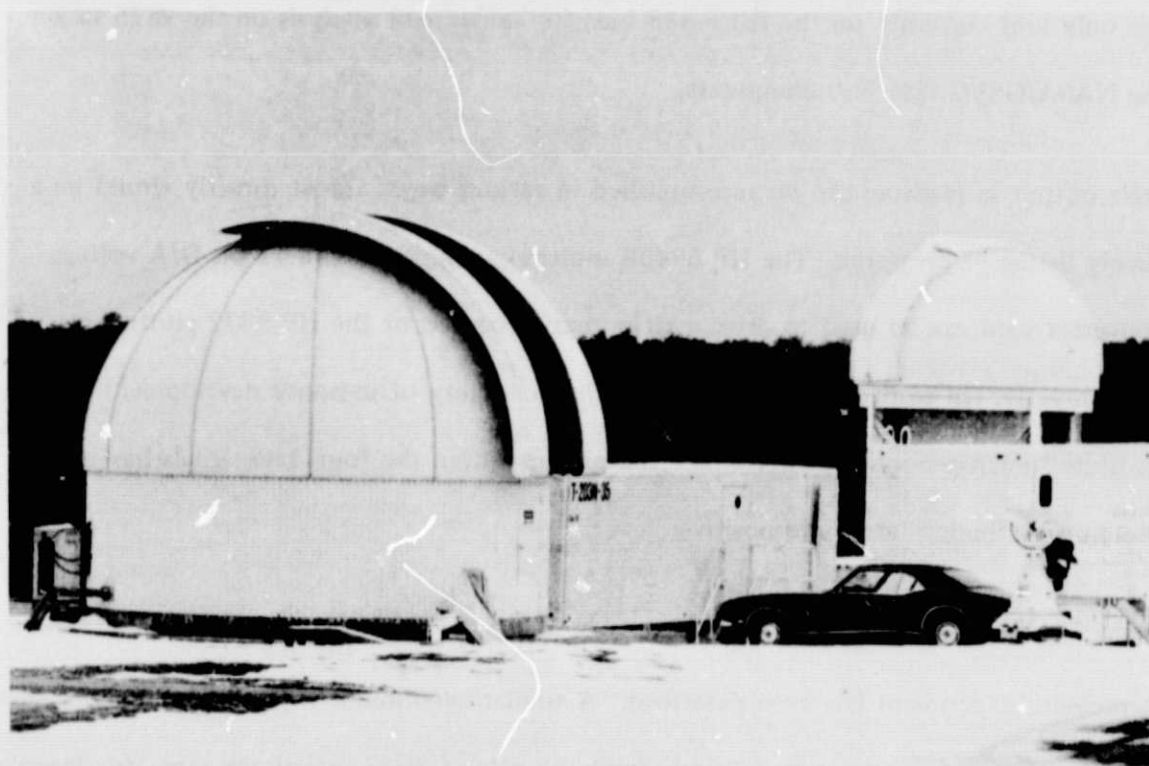


Figure 7. Observatory showing the 400' dome structure (right) where the lasers will be mounted for a bistatic experiment.

depends on aerosol backscatter for profiling. Parallel with the CW experiments, both pulsed lasers and special gating receivers (transient recorders) are being studied for the lidar phase of this work.

We would like to express our appreciation to several people for their ongoing efforts for this project: Geary Schwemmer of Applied Science and Technology who has become one of the keystone workers in all aspects of the program; and Jack Eufon, Tom McGunigal, and Ed Reid of GSFC, along with Dave Grolemond, Jim Fitzgerald, and Don Weaver of Bendix, who are helping get us "on the air" at the Optical Site.

## BIBLIOGRAPHIC DATA SHEET

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